Attachment 2
The Black Warrior Basin

The Black Warrior Basin covers an area of about 23,000 square miles in Alabama and Mississippi. The basin is approximately 230 miles long from west to east and approximately 188 miles long from north to south. Coalbed methane production in the State of Alabama is limited to the bituminous coalfields of west-central Alabama, primarily in Jefferson and Tuscaloosa counties. As of 1996, about 5,000 coalbed methane wells had been permitted in Alabama. Twenty-one coalbed methane fields are operating in the state, with 19 fields (and 90 percent of coalbed gas production) located within the Black Warrior coal basin (Pashin and Hinkle, 1997). Coalbed methane production in the Black Warrior basin is among the highest of any production basin in the US. Historically, typical production has averaged about 300 thousand cubic feet per day per well (Hewitt, 1984; McFall et al., 1986; Schraufnagel et al., 1993). Pashin and Hinkle (1997) estimate that the Black Warrior Basin produces roughly 100 billion cubic feet of gas annually, which is about 20 percent of state gas production from all methods. According to GTI, annual gas production was 112 billion cubic feet in 2000 (GTI website, 2002).

2.1 Basin Geology

Coalbed methane production in the Black Warrior Basin (Figure A2-1) is contained within the Upper Pottsville Formation of Pennsylvanian age (300 million years). The depositional history along the ancient coastline of prehistoric Alabama was characterized by eight to ten "coal deposition cycles" of sea level rising and lowering. Each of these ten geologic "coal deposition cycles" features mudstone at the base of the cycle (deeper water) and coalbeds at the top (emergence) (Pashin and Hinkle, 1997).

The geologic structure is complex, however, and not all cycles/coal groups are present at all locations, due to erosion and structural uplift (Pashin et al., 1991; Young et al., 1993). In general, however, most coalbed methane wells tap the Black Creek/Mary Lee/Pratt cycles, at depths that range from 350 to 2,500 feet deep (Holditch, 1990).

Alabama coalbeds are typically very thin, ranging from less than 1 inch in thickness to 4 feet (in rare cases they are up to 8 feet thick in surface mines) (Horsey, 1981; Heckel, 1986; Eble et al., 1991; Carrol et al., 1993; Pashin, 1994) (Figure A2-2). In the area of coalbed methane development, the Pottsville formation exists at or near the surface, and the depth to commercial coalbeds ranges from surface outcrop to 3,500 feet, depending on location (Figure A2-3).

2.2 Basin Hydrology and USDW Identification

In the area of coalbed methane development in west-central Alabama, the Pottsville formation is an unconfined aquifer. The matrix permeability of Pottsville rocks is low (mudstone, cemented sandstone), but water exists and flows within an extensive system of faults, fractures, and joints. Flow patterns within the Pottsville are strongly controlled by fault- and fold-related isotropic joints and fractures (Koenig, 1989). The close spacing and systematic pattern of cleats, however, makes coals the most productive aquifers within the Pottsville formation (Koenig, 1989; Pashin et al., 1991; Pashin and Hinkle, 1997). In the early 1990's, several authors reported fresh water production from coalbed wells at rates up to 30 gallons per minute (summarized in Ellard et al., 1992; Pashin et al., 1991).

Most recharge to the Pottsville aquifer is precipitation that infiltrates from the surface, but some recharge occurs where streamflow enters the outcrop and moves laterally into the aquifer along folded anticlinal beds (Pashin and Hinkle, 1997) (Figure A2-4). Several researchers also propose upwelling of more saline waters from deeper zones, which takes place along vertical, fault-related, rubble zones (Pashin et al., 1991). Discharge from the Pottsville aquifer is primarily from dewatering of coalbeds due to mining and coalbed methane production (Pashin et al., 1991).

Formation water produced from Alabama coalbed methane wells contains from less than 50 to over 10,000 mg/L total dissolved solids (TDS) (Koenig, 1989; Pashin et al., 1991; Pashin and Hinkle, 1997). Federal UIC regulations define an Underground Source of Drinking Water (USDW) as an aquifer containing less than 10,000 mg/L TDS. Almost all waters of the Pottsville aquifer contain less than 10,000 mg/L TDS, and most waters in the Pottsville flow systems contain less than 3,000 mg/L TDS (Figure A2-5), even within the deeper, methane-target coal seams such as the Mary Lee beds (Figure A2-6). A large proportion of water in the Pottsville aquifer contains less than 500 mg/L TDS (Pashin et al., 1991; Pashin and Hinkle, 1997). Water quality generally decreases with increasing depth (Figures A2-7 and A2-8), and areally is related to the faulting pattern (Figure A2-9) (Pashin et al., 1991; Pashin and Hinkle, 1997). Waters exceeding 10,000 mg/L TDS can be found below 3,000 feet in areas near deep vertical faults, suggesting upwelling from deeper, more saline zones (Pashin and Hinkle, 1997).

2.3 Coalbed Methane Production Activities

Alabama coalbed methane wells are of three distinct types. The first two types, "gob" wells and horizontal wells, are few in number. "Gob" wells are wells associated with mines. The well is drilled to a depth above the mine roof, and when the mine is abandoned, the roof collapses. "Gob" wells produce coalbed methane from the fractured mine debris. A few horizontal wells are drilled from within mines to reduce coalbed methane concentration in advance of a working face. The third type, which includes 98% of all Alabama methane wells, includes vertically drilled wells that utilize mainstream oilfield technologies (Pashin and Hinkle, 1997). Because neither "gob" nor horizontal wells typically are hydraulically fractured, this discussion is limited to vertical wells.

Based on literature reviews and personal communications, most coalbed methane wells are drilled using water or air rotary methods or water-based mud, due to lower cost and concerns that mud fluids will invade the coal. Wells in Alabama are completed with tubing. Water is pumped up the tubing for disposal, whereas gas is produced up the annulus. Wells are drilled to a depth 10-30 feet below the lowest coalbed to create a sump that collects coal fines and allows water to separate from the coalbed methane (Holditch, 1990).

About 95 percent of produced water is disposed by outfall discharge into surface water, via Type II NPDES permits (O'Neil et al., 1989; O'Neil et al., 1993; Pashin and Hinkle, 1997). These permits require some water quality monitoring and limit instream water quality to 230 mg/L TDS (Pashin and Hinkle, 1997). Since 1991, about 5 percent of produced water has been injected for disposal into Class II injection wells (Pashin and Hinkle, 1997). Eight Class II wells are currently active (Alabama Oil and Gas Board, personal communication 2001), disposing coalbed waters into zones between 4,300 and 10,000 feet deep (Ortiz et al., 1993).

Most wells are completed in multiple coal zones using perforations. Some wells are completed in mudstones immediately below a coal zone, rather than within the coal ("limited entry" completions), and a few wells feature un-cased, open-hole completions. Each well is hydraulically fractured to allow communication with the thin coal seams outside of the casing, and most wells are fractured more than once as described below:

- In wells with multiple coal seams present, the hydraulic fracturing process may involve several or multiple stimulations, using from 2 to 5 hydraulic fracture treatments per well (depending on number of seams and spacing between seams); and,

- Many coalbed methane wells are re-fractured at some time after the initial treatment, in an effort to re-connect the wellbore to the production zones to overcome plugging or other well problems (remedial fracture-stimulation). Holditch, 1990; Saulsberry et al., 1990; Palmer et al., 1991and 1991a; Schraufnagel et al., 1991; Holditch, 1993; Palmer et al., 1993a; Spafford et al., 1993; Schraufnagel et al., 1993) (Figure A2-10).

The geometry of hydraulic fractures usually differs between those observed in conventional oil and gas scenarios and those in coalbed methane zones. In conventional hydrocarbon zones, the gas and/or oil are physically "trapped" by the presence of an impermeable confining layer, usually shale. Shale formations present a barrier to upward fracture growth because of their higher "elasticity" and stress contrast (Naceur and Touboul, 1990). Therefore, for conventional fracturing, the vertical growth of fractures out of the target zone may be limited by the presence (i.e., stress contrast) of overlying shales. In conventional gas-well fracture environments, fracture half-length (200-1,600 feet from the well bore) almost always exceeds fracture height (10-200 feet above the perforations).

In the Black Warrior basin, however, the lithologic properties and stress fields of the coal cycles typically produce fractures that are higher than they are long ('length' refers to horizontal distance from the well bore) (Morales et al., 1990; Zuber, 1990; Holditch et al., 1989; Palmer and Sparks, 1990; Jones and Schraufnagel, 1991; Steidel, 1991; Wright, 1992; Palmer et al., 1991a and 1993).

Furthermore, the confining 'shale barriers' of conventional gas reservoirs usually do not exist in many coalbed methane basins. In the Black Warrior basin of Alabama, hydraulic fractures created in coalbed methane deposits are able to grow much higher than some fractures in 'conventional' gas reservoirs. There are three primary reasons for this phenomenon:

- Due to a low modulus of elasticity (i.e., brittleness, stiffness) and complex fracture geometries, high pressures are required to hydraulically fracture coal (500 to 2,000 psi, or 0.7 to 2.0 psi/ft), and high treatment pressure often causes preferential extension of the fracture in the vertical dimension (Jones et al., 1987; Reeves et al., 1987; Morales et al., 1990; Palmer et al., 1991);

- The other rocks within the Pottsville coal cycles (jointed mudstone and sandstone) fracture much more easily than coal (Teufel and Clark, 1981; Saulsberry et al., 1990; Jones and Scraufnagel, 1991; Spafford, 1991). Because there are no significant barriers to fracture height (Simonson et al., 1978; Ely et al., 1990; Palmer et al., 1991), vertical fractures in the Black Warrior basin typically penetrate several thin coal beds and hundreds of feet of intervening rocks (Teufel and Clark, 1981; Hanson et al., 1987; Holditch et al., 1989; Ely et al., 1990; Palmer et al., 1991b; Schraufnagel et al., 1991; Spafford, 1991; Palmer et al., 1993a) (Figure A2-11); and,

- The economics of coalbed methane production requires tall fractures that penetrate several coal seams. The coal seams are typically thin (1 to 12 inches) and economically viable production requires the drainage of as many seams as possible. Because coal seams may be vertically separated by up to hundreds of feet of intervening rocks, operators usually design fracture treatments to enhance the vertical dimension and might perform several fracture treatments within a single well (Ely, et al., 1990; Holditch, 1990; Saulsberry et al., 1990; Spafford, 1991; Holditch, 1993).

Vertical fracture heights in Alabama basins have been measured in excess of 500 feet (Ely et al., 1990; Zuber et al., 1990), and fracture heights of 300 feet are considered typical (Holditch et al., 1989; Lambert et al., 1989; Ely et al., 1990; Saulsberry et al., 1990; Palmer and Sparks, 1990; Spafford, 1991; Palmer et al., 1991 and 1993; Spafford et al., 1993; Gas Research Institute, 1995). Propped fracture lengths, however, are typically modeled or measured as less than 200 feet from the well bore (Wright, 1992, and references of previous sentence).

Although theoretically possible at shallow depth, no specific mention of horizontal fractures was found in the literature reviewed for this study. On the other hand, several researchers conclude (based on pressure behavior during fracturing and several examples where mines penetrated hydraulic fractures) that shallow fractures have a horizontal component as described below:

- Fractures that are created at shallow depth typically have more of a horizontal component and less of the vertical. The vertical component is most likely due to the presence of vertical natural fractures (cleats and joints) as pre-existing planes of weakness from which vertical fractures can initiate. The horizontal component probably results from the overburden stress being the minimum stress, as well as increased likelihood of slippages at lithology or boundary interfaces (David Hill, GTI, personal communication, 2001); and,

- Fractures created deeper can propagate vertically to shallower depth and develop a horizontal component. In these "T-fractures", the fracture tip may fill with coal fines and/or intercept a zone of stress contrast, which causes the fracture to "turn" and develop horizontally at a coalbed-mudstone interface. The height of "T-Fractures" can be 200-300 feet above the perforations (Jones et al., 1987; Morales et al., 1990).

Penetration of the layers above the coal was observed in nearly half of the fractures intercepted by mines underground (Diamond, 1987), but, as coals become shallower, the potential for fracture height growth decreases. In general, horizontal fractures are most likely to exist at shallow depths (less than 1,000 feet). As depths increase, it is more likely that a simple vertical fracture will occur (Gas Research Institute, 1995).

The most common proppant used in coalbed methane treatments in Alabama is sand. The amount of sand injected per fracture treatment ranges from 10,000 to 120,000 pounds (Holditch et al., 1989; Palmer et al., 1991a and 1993). Fracture widths in the formation vary from 0.5 inches to closed (i.e., no proppant emplaced), depending on distance from wellbore and efficiency of the proppant displacement into the length of the fracture (Palmer and Sparks, 1990; Palmer et al., 1993; Steidl, 1993).

Stimulation of fracturing fluid (30,000 to 200,000 gallons per treatment) is injected at a rate of from 5 to 50 barrels per minute (210 to 2,100 gallons per minute) at injection pressures from 500 to 2,300 psi (Palmer et al., 1989 and 1993a; Holditch et al., 1989; Pashin and Hinkle, 1997). The most common component of fracturing fluid is plain water. Several researchers conclude that about 75 percent of all coalbed methane wells in Alabama were fractured using cross-linked gel fluids (e.g., Palmer et al., 1993; Pashin and Hinkle, 1997).

According to service companies, additives that could introduce chemicals exceeding MCLs are no longer used in fracturing fluids as per the Alabama hydraulic fracturing regulation.

Table A2-1 presents some data concerning the general chemical makeup of common fracturing fluids used in Alabama from literature published prior to the Alabama hydraulic fracturing regulation (Economides and Nolte, 1989; Penny et al., 1991). In addition, most gel fluids utilize a breaker compound (usually borate or persulfate compounds or an enzyme, at 2 lb/1,000 gal) to allow post-treatment thinning and easier recovery of gels from the fracture. Several researchers conclude that about 75 percent of all coalbed methane wells in Alabama were fractured using cross-linked gel fluids (e.g., Palmer et al., 1993; Pashin and Hinkle, 1997).

Hunt and Steele (1992) report that environmental regulations restrict local disposal of used fracturing fluids, and that fracturing fluids are transported to regulated disposal sites. Robb and Spafford (1991) reported that acids were used to fracture production zones as shallow as 400 feet deep.

In fracture treatments of wells in homogeneous formations in conventional gas fields, injection is temporary and the majority of fracturing fluid is subsequently pumped back up through the well when production resumes.

There are limited data in the literature concerning the volume of fracturing fluids subsequently pumped back to the well after stimulation has ceased. Mukhergee et al. (1995) observed that for fracture stimulations in multi-layered formations, only 35 to 45 percent of fracturing fluids are recovered. Palmer et al. (1991a) found that only 61 percent of fracturing fluids were recovered during production sampling of a coalbed well in the Black Warrior basin, Alabama, and projected that 20 to 30 percent would remain in the formation.

2.4 Summary

Coalbed methane development and hydraulic fracturing in the Black Warrior basin of Alabama takes place within a USDW, the Pottsville formation. Almost all of the waters of the Pottsville formation contain less than 10,000 mg/L TDS. Most waters contain less than 3,000 mg/L, and a large proportion contain less than 500 mg/L. Pashin et al. (1991) and Ellard et al. (1992) reported "fresh" water production from coalbed zones at rates of up to 30 gallons per minute. Alabama regulates hydraulic fracturing of coalbed methane wells. Per that regulation, service companies no longer use additives that could introduce chemicals exceeding MCLs into USDWs.

In the Pottsville formation, the lack of a significant vertical barrier provides for fracture height growth that can be essentially unconfined, and fracture heights approach 600 feet. Fracture heights of 300 feet are considered typical (Holditch et al., 1989; Lambert et al., 1989; Ely et al., 1990; Saulsberry et al., 1990; Palmer and Sparks, 1990; Spafford, 1991; Palmer et al., 1991 and 1993; Spafford et al., 1993; Gas Research Institute, 1995).

Table A2-1. Chemical Components Previously Used in Typical Fracturing/Stimulation Fluids for Alabama Coalbed Methane Wells

Type of Stimulation Fluid	Composition	pH
Fluids		
Hydrochloric acid	15% HCl water solution	<1-3
"Slick" water	water-soluble solvent as viscosity reducer (% unknown)	NA
Diesel oil	NA	NA
Gels[1]		
R-F	3% resorcinol, 3% formaldehyde, 0.5% KCl, 0.4% $NaHCO_3$	6.5
Pfizer Flocon 4800	0.4% xanthan, 154 ppm Cr^{3+} (as $CrCl_3$), 0.5% KCl	4.0
Marathon MARCIT	1.4% polyacrylamide (HPAM), 636 ppm Cr^{3+} (as acetate), 1% NaCl	6.0
DuPont LuDox SM	10% colloidal silica, 0.7% NaCl	8.2
CPAM crosslinked with Pfizer Floperm 500	0.4% cationic polyacrylamide (CPAM), 1520 ppm glyoxal, 2% KCl	7.3
Drilling Specialties HE-100 Crosslinked	0.3% HPAM-AMPS, 100 ppm Cr^{3+} (as acetate), 2% KCl	5.0

[1] Gels are typically mixed at a ratio of 40 lbs. per 1000 gal. water; compositions shown are "as mixed".

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SPE = Society of Petroleum Engineers

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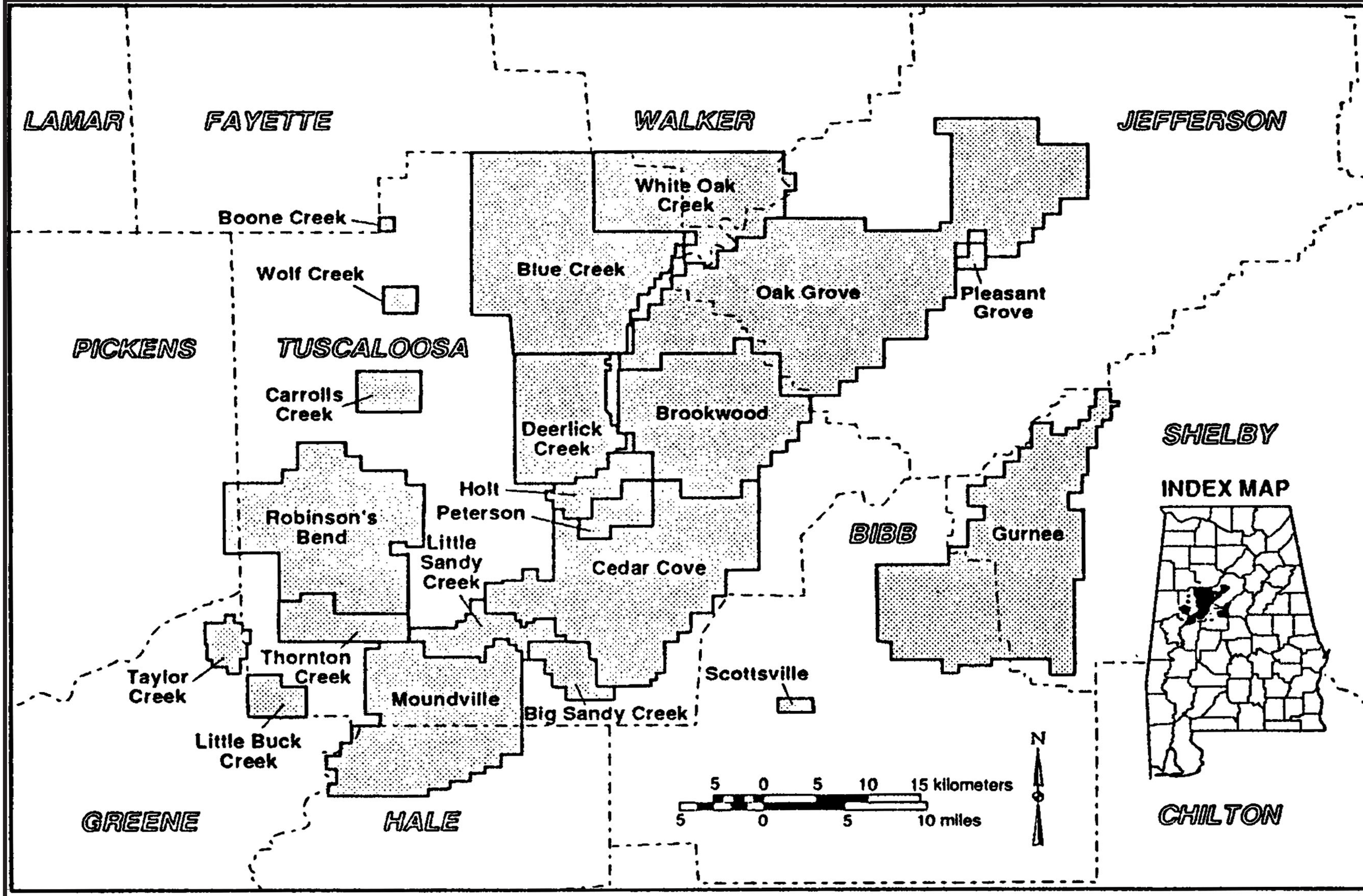
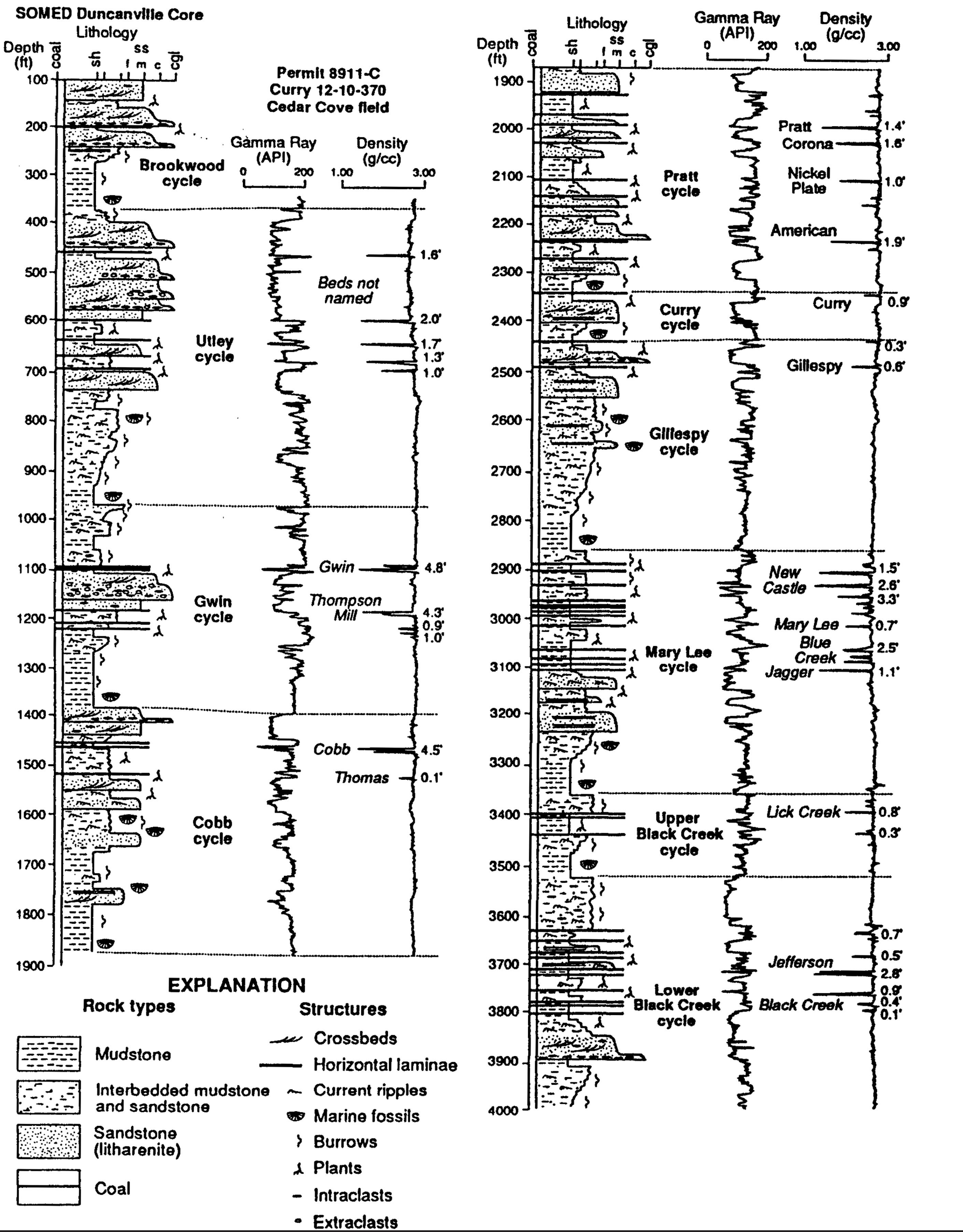


Coalbed Methane Fields of Alabama (Pashin and Hinkle, 1997)

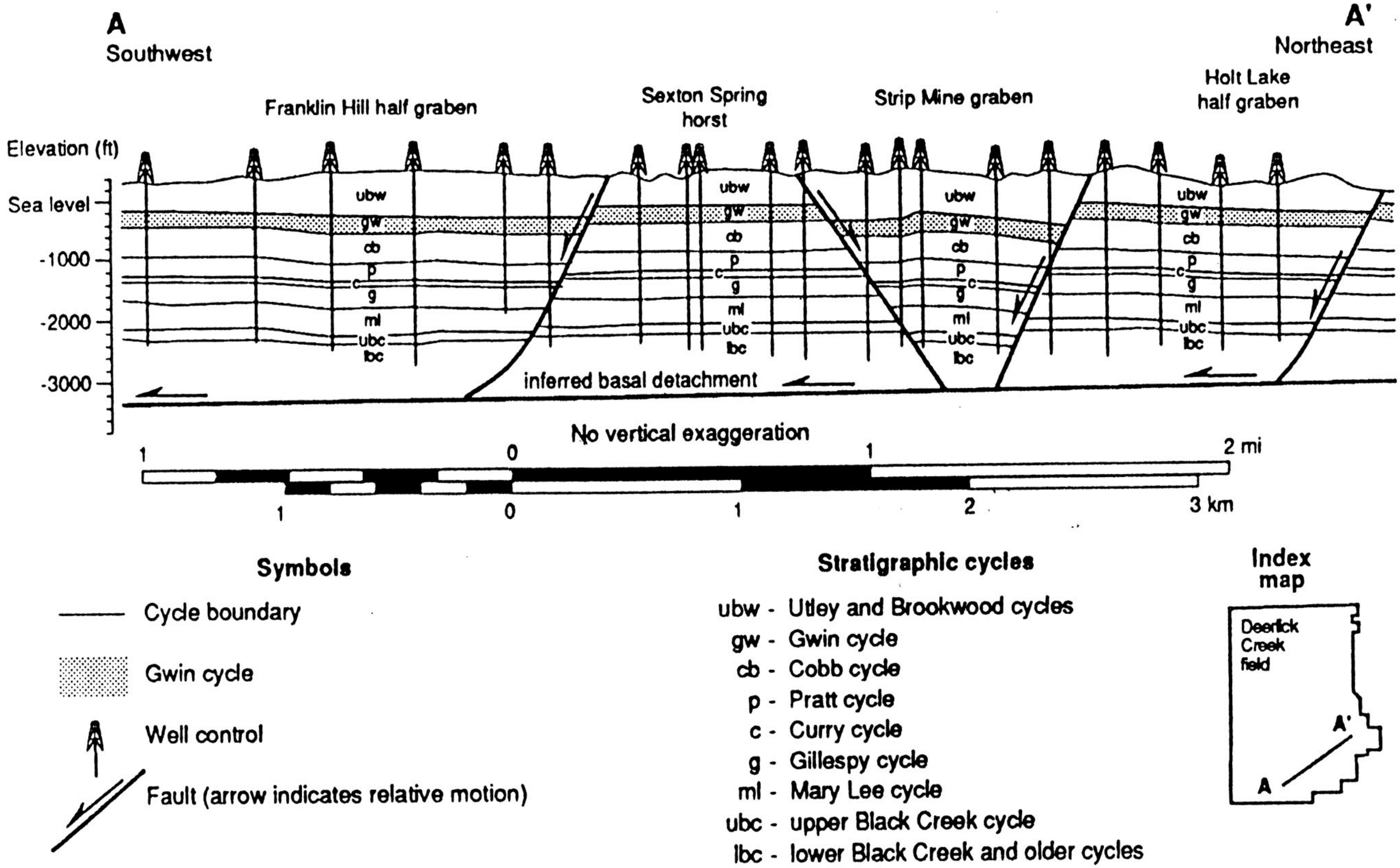
7/14/01 kk 1027-HF-BW-1.cdr	Figure A2-1



Coal Cycles of the Pottsville Formation in the Black Warrior Basin (Pashin and Hinkle, 1997)

7/14/01 kk 1027-BW-2.cdr

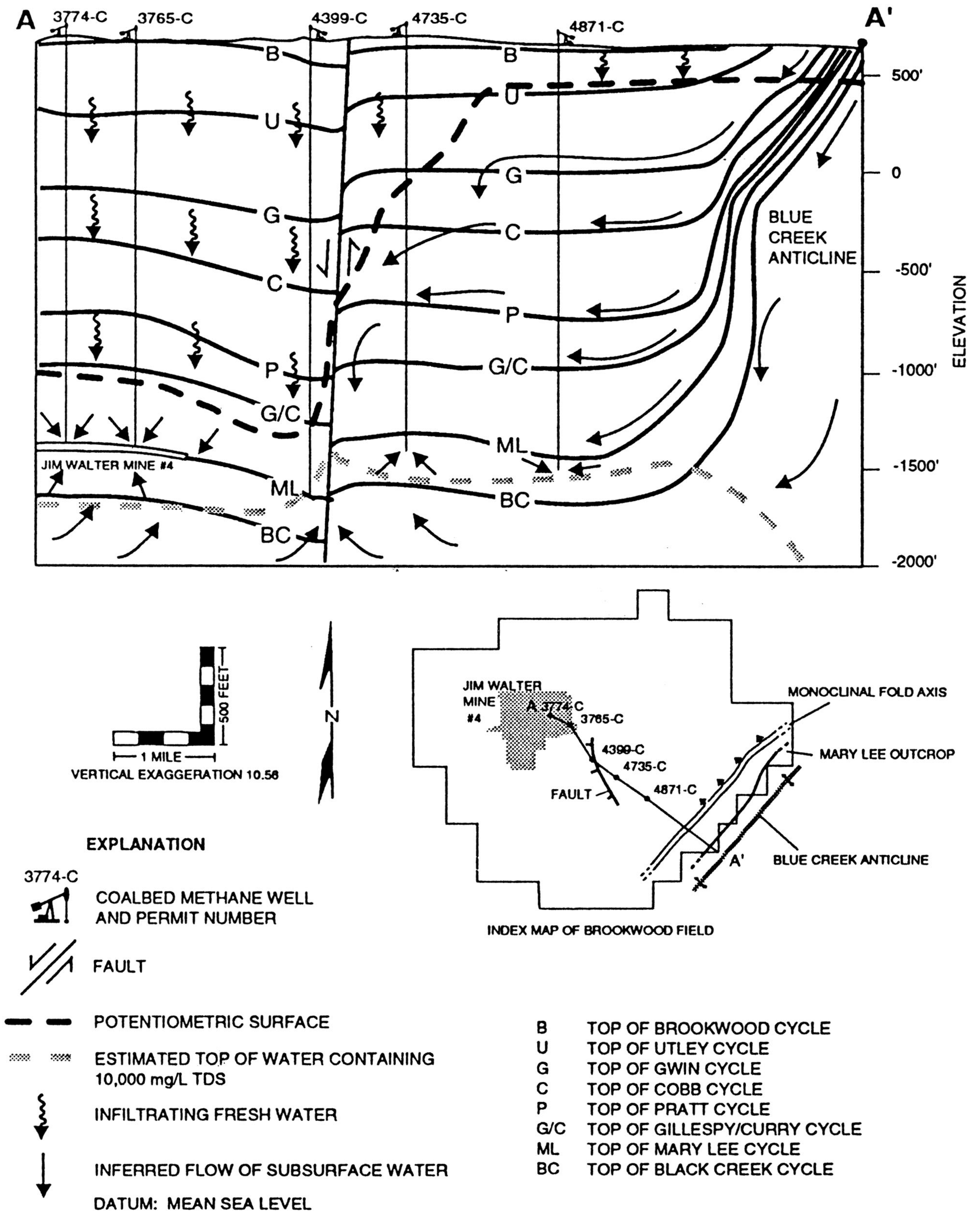
Figure A2-2



Cross-Section of the Pottsville Formation in the Deerlick Creek Field (Pashin and Hinkle, 1997)

7/14/01 kk 1027-HF-BW-3.cdr

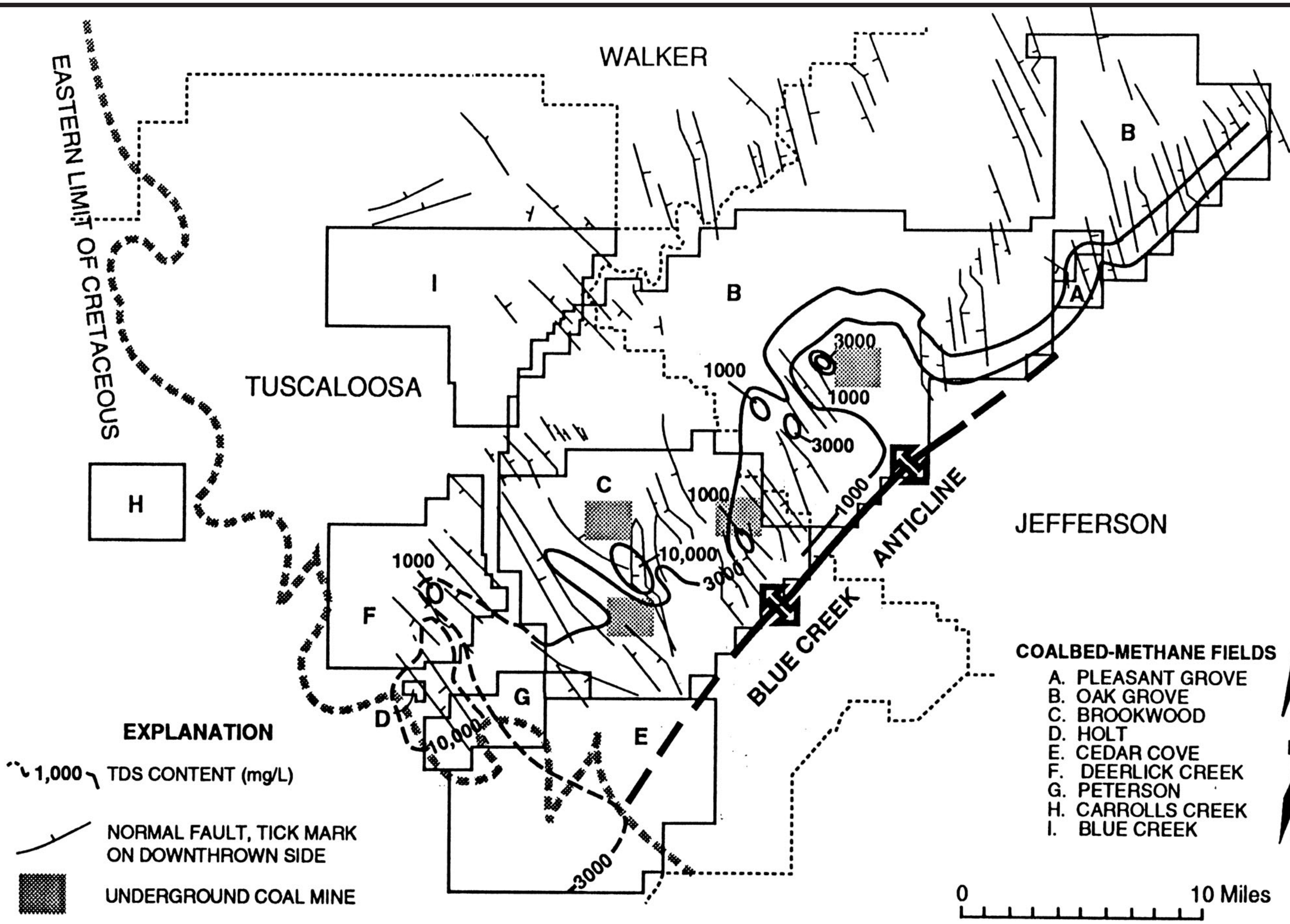
Figure A2-3



Hydrogeologic Cross-Section of the Pottsville Formation in the Brookwood Field
(see Figure 2-1 for Field Location) (Pashin and Hinkle, 1997)

7/14/01 kk 1027-BW-4.cdr

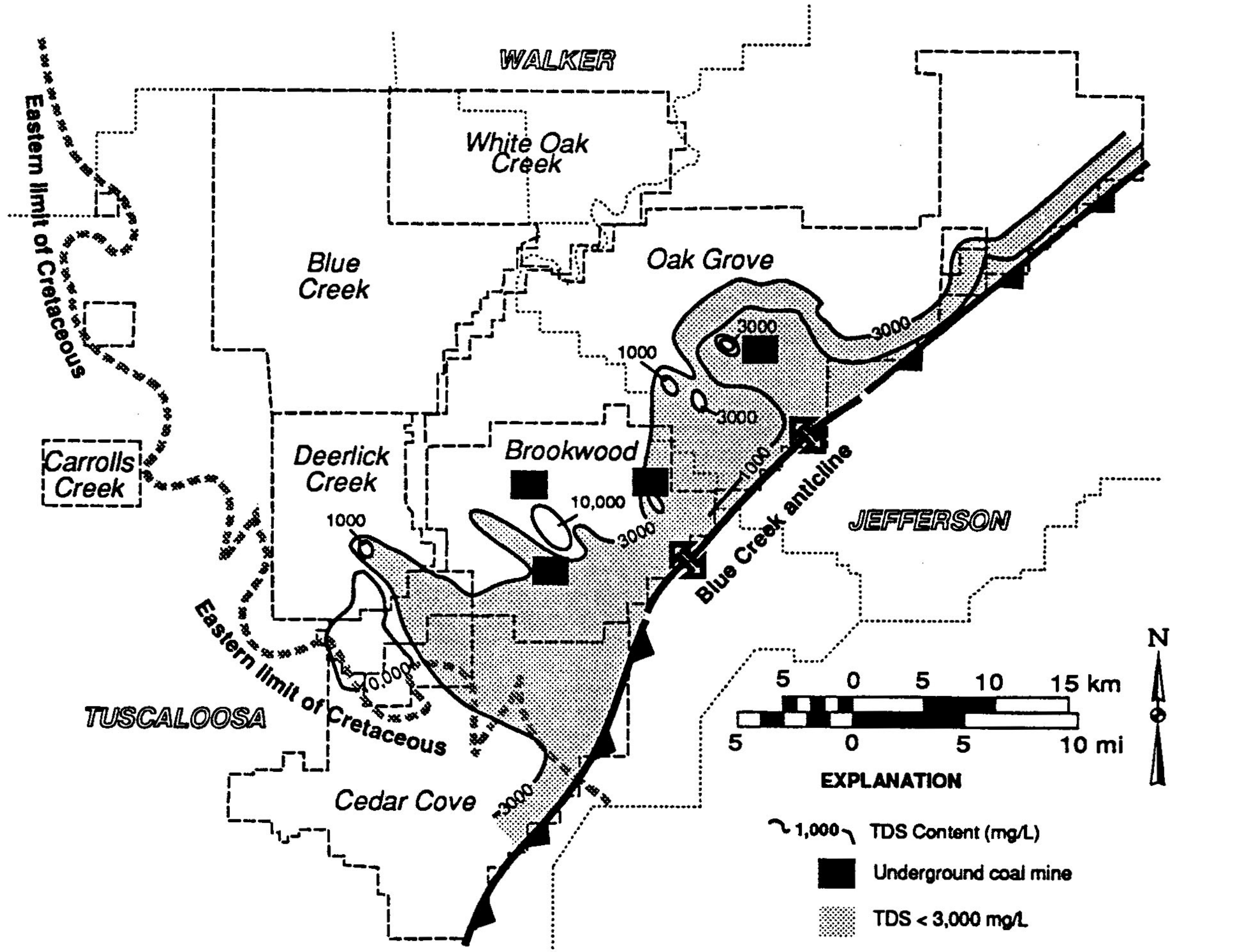
Figure A2-4



TDS concentration of Pottsville Aquifer, Black Warrior Basin, Alabama (Pashin and Hinkle, 1997)

7/14/01 kk 1027-HF-BW-5.cdr

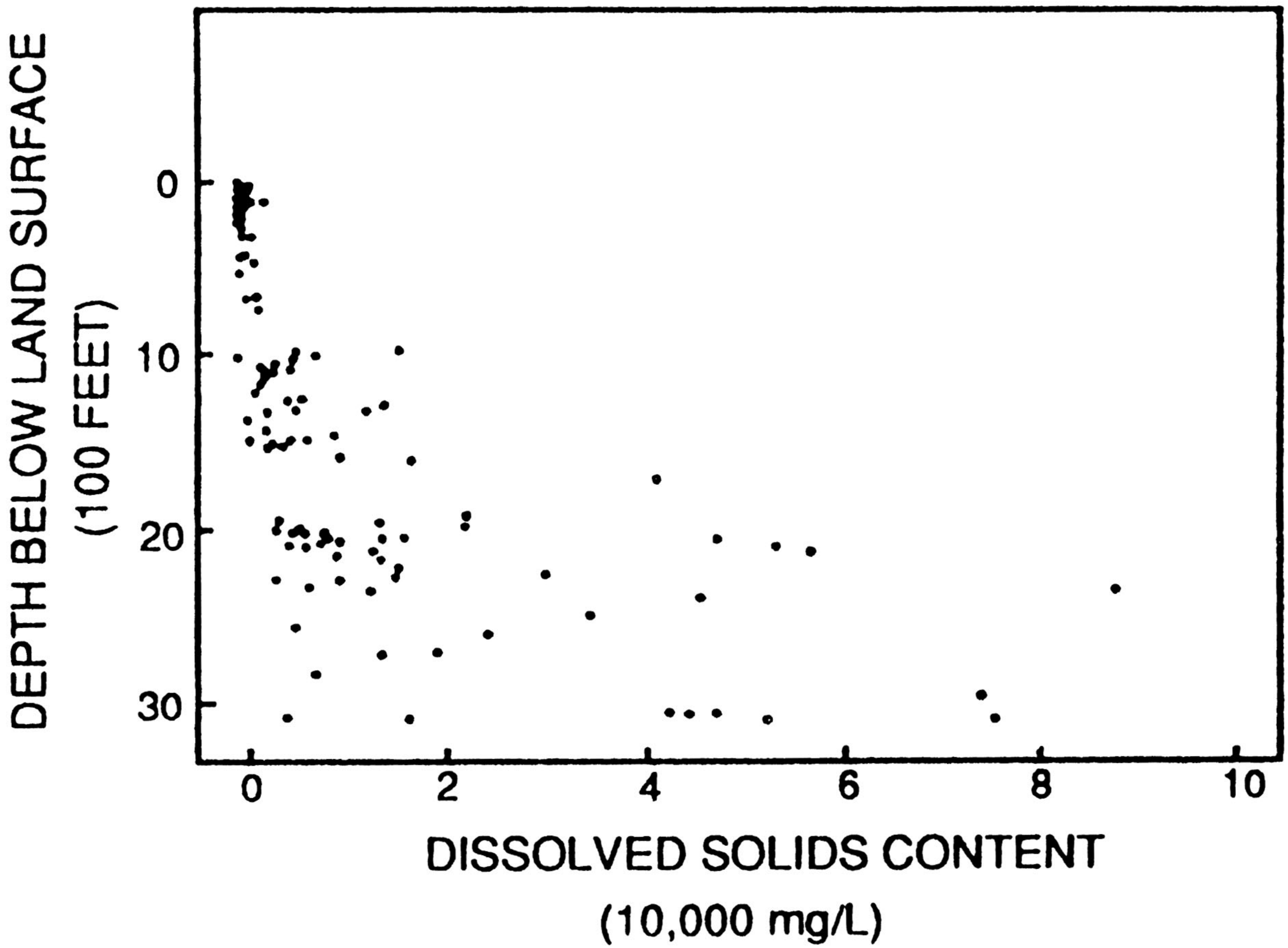
Figure A2-5



TDS Concentration of the Mary Lee Coal Seam of the Pottsville Aquifer in the Eastern Part of the Black Warrior Basin, Alabama (Pashin et al., 1991)

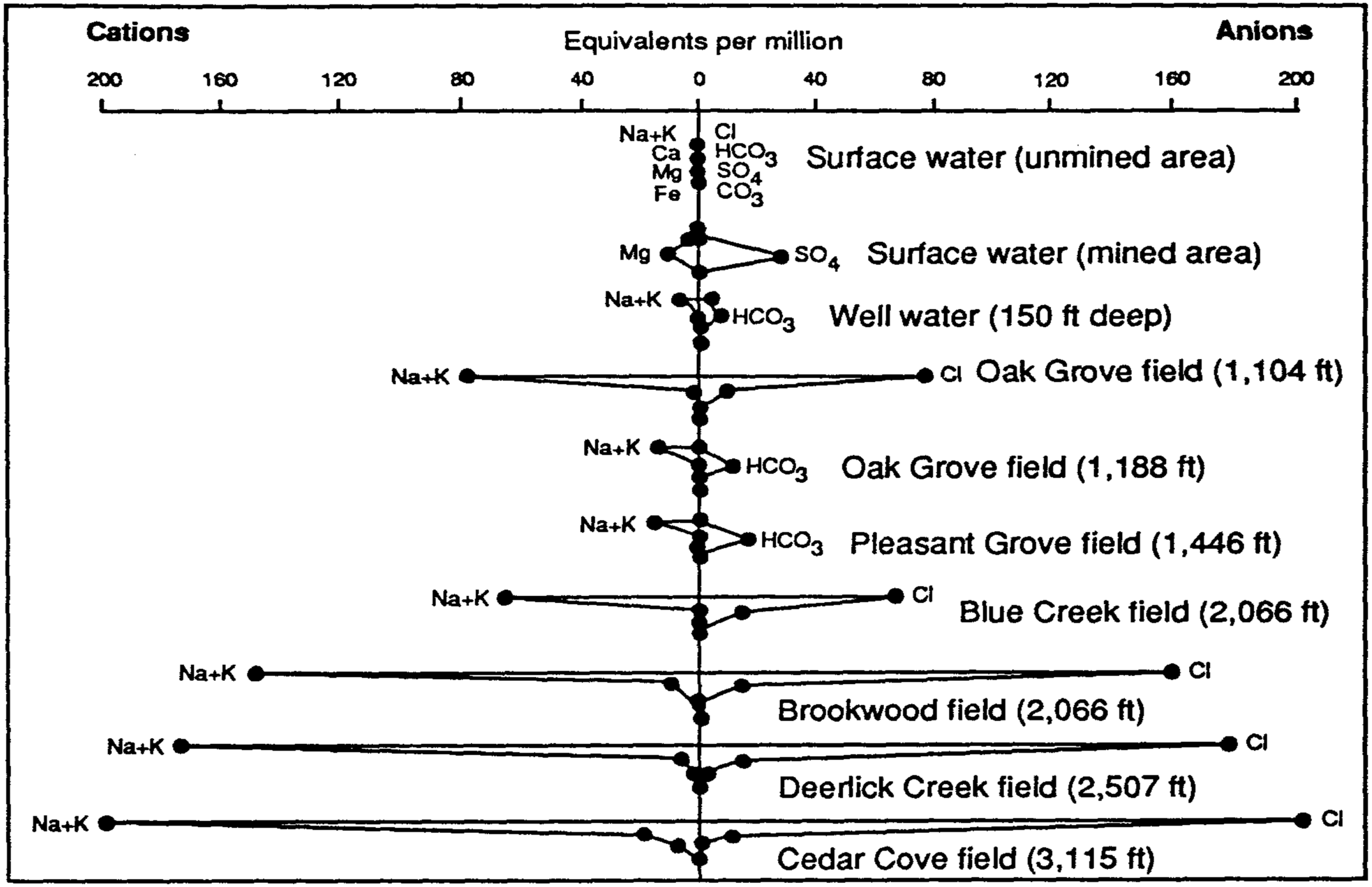
7/14/01 kk 1027-HF-BW-6.cdr

Figure A2-6



Generalized Increase in TDS Concentration with Depth in the Pottsville Aquifer
Black Warrior Basin, Alabama (Pashin et al., 1991)

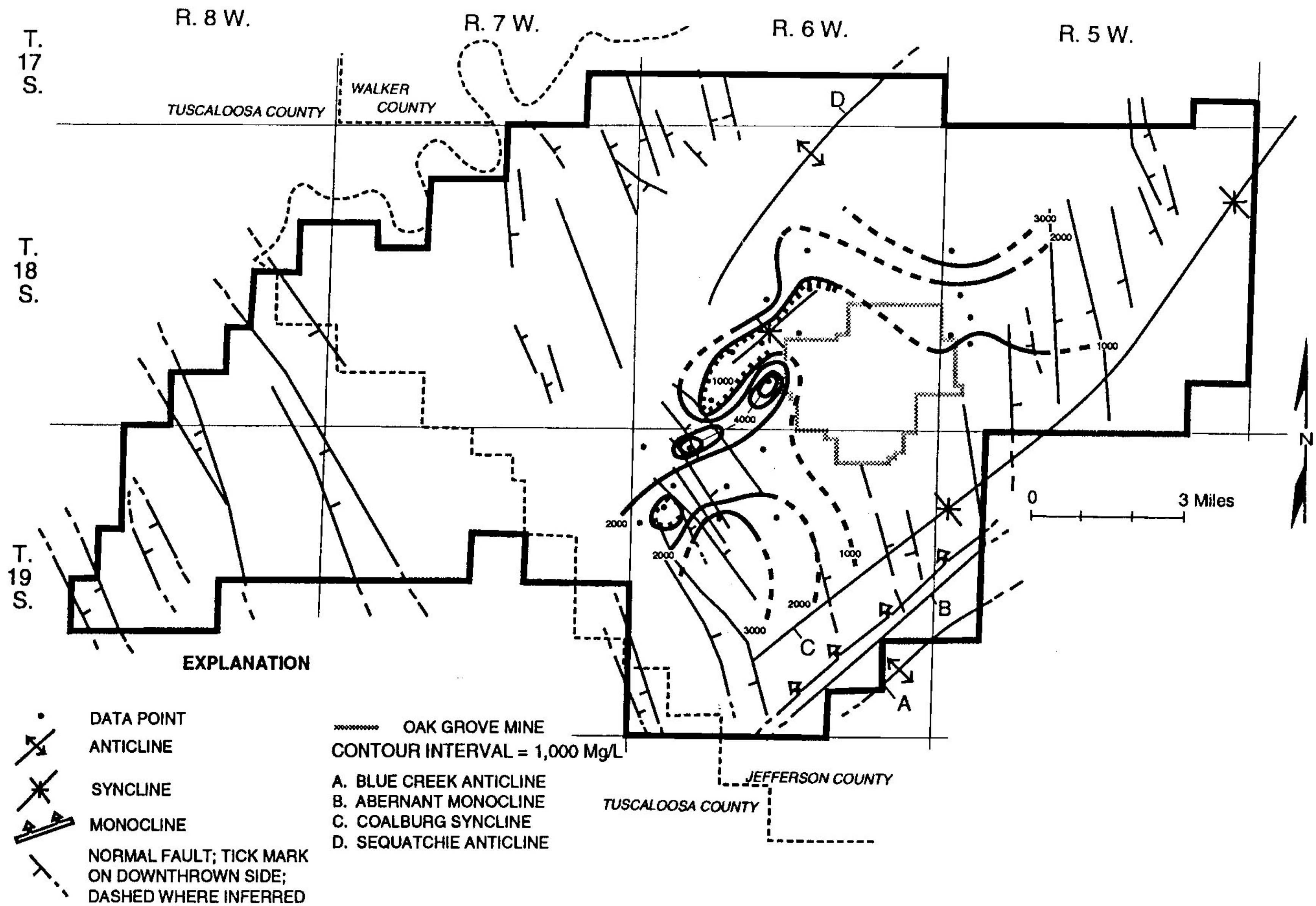
7/14/01 kk 1027-HF-BW-7.cdr	Figure A2-7



"Stiff" Diagram of Water Salinity (Pashin et al., 1991). The diagram indicates that most water samples contain less than 10,000 mg/L TDS (except near a few faults), and the salinity generally increases with depth in the Pottsville Aquifer, Alabama. Note that as mg/L of NaCl, the "Equivalent per Liter (epm)" units of the table correspond to 2337 mg/L (40 epm), 4675 mg/L (80 epm), 7012 mg/L (120 epm), 9350 mg/L (160 epm), and 11,688 mg/L (160 epm). NaClis, by far, the dominant species of most Pottsville water samples, and mg/L as NaCl closely approximates mg/L TDSs

7/14/01 kk 1027-HF-BW-8.cdr

Figure A2-8



Relationship of Water Salinity to Structural Features in the Oak Grove Field, Black Warrior Basin, Alabama (Pashin and Hinkle, 1997).
In general, water containing more than 3,000 mg/L TDS is related to upwelling of saline water near a few geologic faults

7/14/01 kk 1027-HF-BW-9.cdr

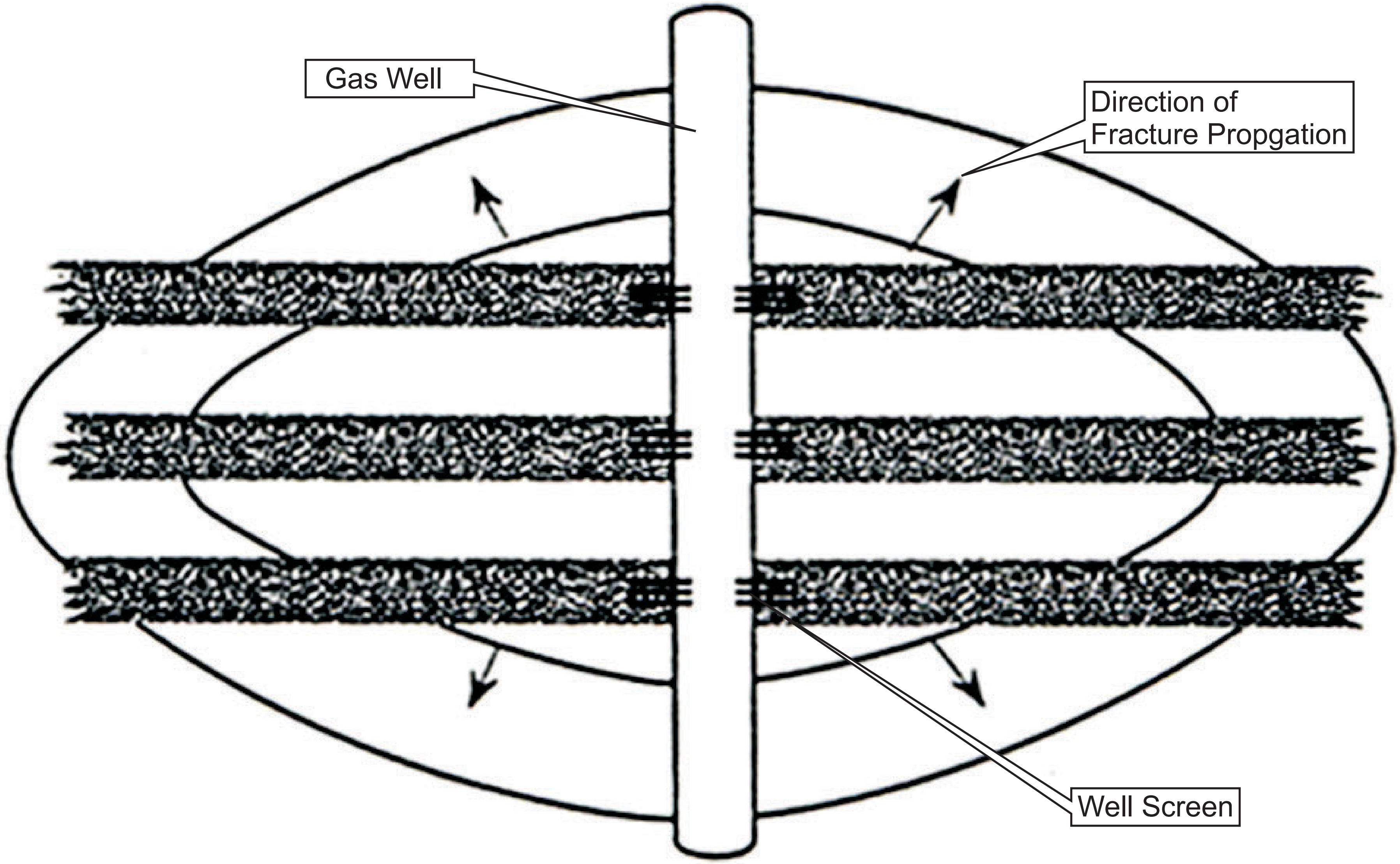
Figure A2-9

Field*	Number of Producing Groups	Coal Group	Depth Range (ft)	Number of Separate Stimulations
Oak Grove	2 or 3	Pratt Mary Lee** Black Creek	500–2500	2 or 3
Deerlick Creek (Lambert et al., 1987, 1990)	3		1000–3000	3
Cedar Cove (Sparks and Richardson, 1991)	4	Cobb Pratt Mary Lee** Black Creek	2000–3500	4
Moundville (Ely et al., 1990)	Up to 6 or 7†	Brookwood Utley Gwin Cobb Pratt Mary Lee** Black Creek	3000–5000	3–6

Productive Coal Seams and the Typical Number of Stimulations Per Well as of 1993, Black Warrior Basin, Alabama (Palmer et al., 1993)

7/14/01 kk 1027-HF-BW-10.cdr

Figure A2-10



Sketch of a Vertical, Unconfined Fracture Typical of the Black Warrior Basin (Palmer et al., 1991)

7/14/01 kk 1027-HF-BW-11.cdr

Figure A2-11